CALIFORNIA
ENERGY
COMMISSION

ENERGY INNOVATIONS SMALL GRANT PROGRAM
Industrial, Agriculture and Water
End Use Energy Efficiency

Modeling Greenhouse Temperature for Energy Efficient Production

FEASIBILITY ANALYSIS

July 2003
P500-03-054F

Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which $2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to $75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
  - Appendix A: Final Report (under separate cover)
  - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission’s Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission’s Web site at http://www.energy.ca.gov/research/index.html.

Executive Summary

Introduction

California is the leading state in the US floriculture industry, with wholesale value over 700 million dollars per year. With more than 115 million ft^2 area under greenhouse cover, California has the largest area of protected crop production facilities in the nation [National Agricultural Statistics Service, USDA. 1998].

Greenhouse agriculture requires considerable energy for cooling in the summer and heating in the winter. While computers have been incorporated into most greenhouses, no significant environmental control software exists. Each crop that might be grown in a greenhouse has different temperature requirements. Proper use of an accurate crop model embedded within greenhouse environmental control software will enable achievement of the optimum energy efficiency for the greenhouse crop combination.

Objectives

The goal of this project was to determine the feasibility of embedding a sufficiently detailed and accurate model within the greenhouse environment control software to enable optimum energy efficiency for the greenhouse crop combination. The researchers established the following project objectives:

1. Create and integrate greenhouse climate models with crop models.
2. Validate the integrated model.
3. Develop general-purpose energy management software tools that growers could use to assist in greenhouse energy management.

Outcomes

1. A full-sized, large-scale simulation model was developed that simulates the greenhouse climate in relation to the control objectives, the outside climate, the crop growing in the greenhouse, and the various management practices. This model was then implemented on a computer simulation system. The size and complexity of the model was such that the high-end computer workstation it was hosted on would only simulate short time frames. The researcher could not fully exercise the computer model due the excessive memory demands of the program, even when running on a high capacity workstation. Evaluation of this implementation was not completed.

2. Partial validation of the model was performed. The simulation model behavior was satisfactory in most areas except for its inability to accurately predict the air temperature and humidity inside the greenhouse in the winter.

3. A software tool was developed that allows growers to calculate temperature set points in relation to rose-crop development for cut-flower roses. Presentations and training sessions at national grower meetings (March 30 2001; Denver CO) have been conducted to assist growers in using the software. The software tool was made available to the public through publication on the web to allow easy access by the greenhouse operators. The Principal Investigator has indicated that this software tool has been downloaded for use by rose growers in California.

Conclusions

1. Considerable insight was gained into the many variables that impact greenhouse thermal properties. The complexity of the modeling and simulation was greater than originally anticipated. The size and complexity of the model and its inability to run effectively, even on a high end computer workstation, makes the model impractical for real time greenhouse control in its current configuration. The accuracy of the integrated model was impacted by errors contained in existing models/data.

2. Further work is needed to validate and optimize the model for accuracy before it can be used for comprehensive energy simulations. Feasibility of integrated greenhouse climate models with crop models has yet to be established.

3. Due to the complexity of the various crop models it may not be possible to create general-purpose energy management software tools that could be applied to a variety of crops. Instead, it appears that the software tools will need to be tailored to specific crops, which will require considerable research and development.

Benefits to California

Greenhouse growers will benefit directly from the tool that was developed as part of objective 3 of this project. The tool is particularly targeted to cut-flower rose growers, to assist them in selecting temperature set-points that will allow them to schedule crop maturation to coincide with holiday sales. This tool allows growers to maximize profitability by optimizing productivity through precise energy management. Energy use by cut flower growers may be reduced by use of this energy control tool.

Recommendations

The simulation system, as an analytical tool, will require considerably more work before it will result in widespread practical applications for greenhouse energy management. Additional work is needed that would allow the model to run effectively on a standard computer. The model needs additional development to make it more accurate in the areas of noted deficiency. Specific crop models need to be developed that can be integrated into the greenhouse climate model.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven typ es of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: http://www.energy.ca.gov/research/innovations and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market

The presentations and training sessions conducted in Denver in late March, 2001, and its ready availability on the Internet will help to bring the rose grower software tool into broader use.

Engineering/Technical

Though progress was made, complete success was not achieved. It appears that the technology is feasible but it is by no means certain based on results achieved. Significant advances were made in the mathematical description of the greenhouse model and of crop models. However, the implementation of these mathematical models as a computer program simulating the greenhouse and crop environment was not sufficiently robust to fully support the intended analysis.

The Joseph Hill Foundation has committed funds to further work on the rose grower software.

Legal/Contractual

There are no known legal or contractual issues outstanding for this project.

Environmental, Safety, Risk Assessments/ Quality Plans

This is the stage of development to discover whether or not there are pertinent unknown issues which may arise in later stages. There is no indication that Quality Planning has been addressed, hence no issues were identified. Drafting of the Quality Plan is needed prior to initiation of Stage 4 development activity. Quality Planning addresses the following: Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, Product Safety and Environmental.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere.

Production Readiness/Commercialization

There was no mention of a commercializing partner, none has been selected, hence no commitment obtained.

Public Benefits

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the California Greenhouse operator ratepayer from this research was increased affordability of electricity. This was accomplished by enabling more efficient utilization of the power resource by the greenhouse operator ratepayer. Specifically targeted tools, such as the rose grower's tool, allows the ratepayer to precisely apply electrical energy to most efficiently govern the rose's growth environment and maturation timing.

Technology Transfer

The principal investigator for this project has performed the following Technical transfer activities:

- Public presentations and training sessions were conducted in Denver in March 2001 to assist growers in the use of the software tools.
- Obtained follow-on funding from Joseph Hill Foundation to extend the model to incorporate additional cut rose varieties.
- Published the completed rose-crop software on the Internet to facilitate access by the greenhouse operators. An estimated 200 growers have evaluated the tool.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

Appendix A to FAR 99-08

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

MODELING GREENHOUSE TEMPERATURE FOR ENERGY EFFICIENT PRODUCTION

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Grant #: 99-08
Grant Funding: $75,000
Term: September 1999 – December 2001
PIER Subject Area: I/A/W End Use

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Table of Contents

Abstract

The objective of this project was to develop information regarding energy-efficient maintenance of greenhouse temperatures. Greenhouses require considerable energy for cooling in the summer and heating in the winter. Each crop that might be grown in a greenhouse has different temperature requirements. The ultimate goal was two fold: (1) to integrate models for the greenhouse environment with a crop model and (2) to develop tools that growers could use to assist in greenhouse energy management.

A large-scale dynamic simulation model was developed using STELLA that simulates the greenhouse climate in relation to the control objectives, the outside climate, the crop growing in the greenhouse, and the various management practices. Details of the greenhouse energetics are encapsulated in the simulation model which is represented graphically in this report. While the simulation model behavior appears to be consistent with expected greenhouse behavior in most ways, further work is needed to deal with some inconsistencies and to validate the model and to do further model calibration.

A software tool was developed that allows growers to calculate temperature set-points in relation to rose-crop development. The software is disseminated via a web site and presentations and training sessions. The tool is targeted to cut-flower rose growers, to assist them in selecting temperature set-points. This research will also require further work in software development and calibration.

Executive Summary

1. Introduction

This project was needed to develop information with regard to energy-efficient maintenance of greenhouse temperatures. Greenhouse agriculture requires considerable energy for cooling in the summer and heating in the winter. Each crop that might be grown in a greenhouse has different temperature requirements. The goal of this study was to develop a model system that could be used to evaluate the energy requirements of a particular crop in relation to a the greenhouse environment.

2. Project Objectives

The ultimate goal was two fold: (1) to integrate models for the greenhouse environment with a crop model and (2) to develop tools that growers could use to assist in greenhouse energy management.

3. Project Outcomes

A full-sized, large-scale simulation model was developed that simulates the greenhouse climate in relation to the control objectives, the outside climate, the crop growing in the greenhouse, and the various management practices. We were unable to complete this system to the desired level; in particular the current version has not undergone validation. The simulation model behavior, however, appears to be consistent with expected greenhouse behavior in most ways.

A software tool was developed that allows growers to calculate temperature set-points in relation to rose-crop development. The software is disseminated via a web site and should be easy for growers to use. Presentations and training sessions at national meetings (March 30 2001; Denver CO) are already planned to assist grower in using the software.

4. Conclusions

We gained considerable insight into both greenhouse energetics and large-scale simulation modeling. Details of the greenhouse energetics are encapsulated in the simulation model which is represented graphically within this report. Further work is needed on the model.

5. Benefits to California

Greenhouse growers will benefit directly from the spin-off tool that we developed as part of this work. The tool is particularly targeted to cut-flower rose growers, to assist them in selecting temperature set-points that will allow them to schedule their harvests to coincide with holiday sales, even if drastic changes are needed in terms of energy use.

6. Recommendations

The simulation system as an analytical tool will require considerably more work. We learned that many facets of the system require calibration despite the fact that others had calibrated these components in the past. There are several key areas where the model behaves incorrectly (in comparison with reality). We must solve these inconsistencies before further use of the tool can be made.

The software developed for rose growers also require considerably further work. This work is being funded by the Joseph Hill Foundation, which funds research on cut-flower roses. This work will consist of calibration of the software for numerous rose varieties and further software development.

Main Report

1. Introduction

The objective of this project was to develop a simulation model for greenhouse temperature with the idea of improving greenhouse energy efficiency. We also sought to create tools that greenhouse growers can use to allow them to manage their production system as efficiently as possible.

The simulation work consisted of two parts: (1) using a computer simulation system to describe the greenhouse system and (2) the collection of greenhouse data to validate this model. For the first part we based our work on a model we developed for a glass greenhouse at UCDavis (Li, L.-Y. 1999) and added the needed elements to make it suitable for use with a wider range of greenhouses. One innovative feature of this research was the combining of models for greenhouse climate with a cut-flower rose crop model. For the second part an extensive data set was collected in a rose greenhouse, incorporating a wide range of variables; this work focused on using a different greenhouse from one that had been used in the earlier work. By focusing on roses were able to make synergistic use of results from various research projects that were running concurrently.

The development of a tool that growers can use is based the portion of our rose crop modeling work that describes the relationship between crop development and greenhouse air temperature. This tool is being disseminated by internet web site and provides growers with a tool they can use to deal with the current energy crisis (their energy costs have doubled in the last few month).

2. Project Approach (Experimental Design)

2.1 Rationale

Greenhouse air temperature is an indicator of its overall thermal status, therefore, any physical process that affects the thermal exchange between the greenhouse and its surroundings should be taken into account, and should thus be monitored in this experiment. The energy exchange takes place as three forms: radiation, conduction and convection; all can be found in greenhouse systems.

The greenhouse is a transparent structure, its primary energy source is solar radiation. Light sensors are used to measure the global solar radiation striking the greenhouse glass, that which is reflected and absorbed by the glass, that which is shaded by the greenhouse structures, and that reaching to crop canopy. Thermal exchange between greenhouse components through long wave radiation can be calculated by measuring temperatures of objects that have direct exposure to each other.

Thermal conduction occurs as a result of temperature differences. Thermal conductance which is of significance to greenhouse energetics includes heat fluxes in soil and through glasses. Soil heat flux is determined by the soil physical properties and temperature gradient. Thermal conductance through glass is dominated by thermal properties of the glass and the temperature difference between inner air and outer air. To obtain the information needed to calculate soil heat flux and thermal conductance through glass, temperature sensors were placed at various depths in the soil, and on both sides of greenhouse glass.

Convection is a form of thermal exchange due to the movement of air molecules or air eddies with different temperatures. Both free convection and forced convection occur in greenhouse systems. The free convection occurs in the boundary layer near a surface if the temperature gradient is moderate. Forced convection typically occurs through air movement created by exhaust and horizontal-air-flow fans, or through air movement into the greenhouse through ridge vents. To calculate convective thermal exchange, thermocouples were used to measure the thermal status of various compartments of the greenhouse system, such as inner air, soil surface and glass. It is also necessary to monitor cooling control actions, such as the on/off action of cooling fans and open/close action of ridge vents, as well as the duration of each stage. This was accomplished by clamping Alternating Current (AC) sensors to the wires that power the fans, and by mounting a displacement sensor on the ridge vent.

Heating is an external source of energy input into the greenhouse that is also a primary concern for greenhouse energy efficiency. The amount of heating can be calculated by monitoring the flow rate of hot water into the system and the temperature changes before and after the circulation. A flow meter was installed in the heating pipe, and water temperatures were measured at locations where the water enters and exits the system.

2.2 Overview of the experimental set-up

The greenhouse used for this study was located at the Department of Environmental Horticulture at the University of California in Davis, CA. It is a typical even-span greenhouse. The climate in the greenhouse was monitored and controlled by a central computer running GEM3 (“Greenhouse Environment Monitor”) software by the firm that built the greenhouse environment control system (Q-Com, Corp). The greenhouse was occupied by cut-flower rose plants used for this and other studies.

The greenhouse was heated with a hot water circulating system, and cooled by ridge vents and pad-and-fan evaporative cooling system. The sensed air temperature is compared with the set-points for the greenhouse climate. Environmental control actions by the control system were based on the difference between actual temperature measurement and its set-point. The temperature control involves various cooling and heating stages. For example, cooling can be achieved through opening of ridge vents, running cooling fans with or without water on the cooling pads. The greenhouse used in this study had only one heating stage, providing its full heating capacity once it was turned on.

Environmental sensors were placed at various locations, both inside and outside of the greenhouse (Fig.1). Light sensors (Quantum sensors, LI-COR Inc.) were used to measure (1) the global shortwave radiation striking on the greenhouse glass; (2) the reflected shortwave radiation by greenhouse structures; (3) the radiation just below the greenhouse glass and (4) the radiation at the top of crop canopy. The difference between (3) and (4) is that when the sun moves across the sky, the greenhouse structure may cast shadows on the light sensor at the top of crop canopy, but not at the one that is immediately below the glass. Thermocouples were used to measure temperatures of air, glass, soil and plants at various locations. Thermocouples measuring air temperatures were shielded from direct solar radiation. Air temperatures were measured both outside

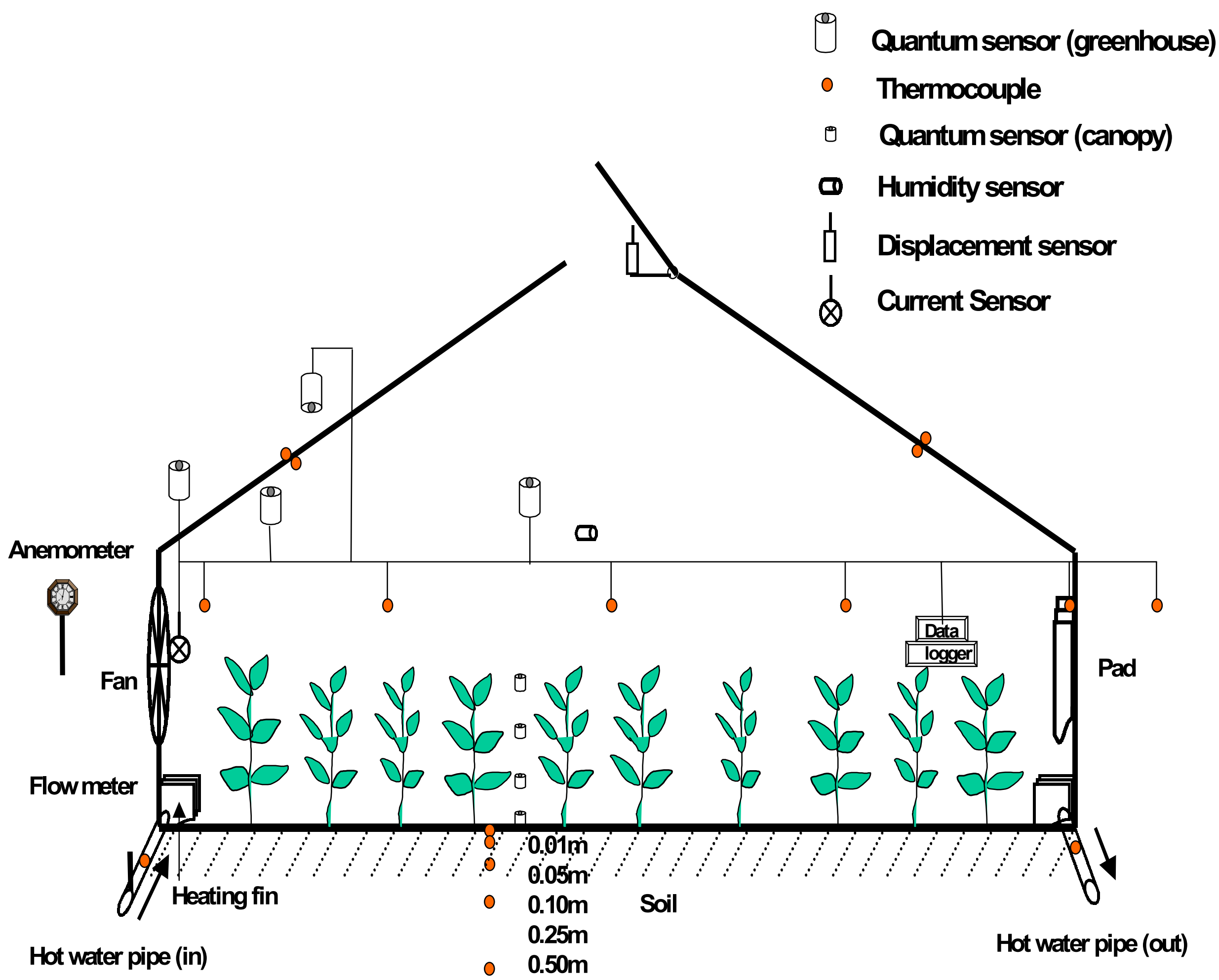

Figure 1 Experimental setup: sensors and their location

and inside the greenhouse. Five temperature sensors are located inside the greenhouse along the temperature gradient imposed by the cooling system. The glass temperature was measured with thermocouples both on the interior and exterior of the greenhouse. To ensure accurate measurements, silicon heat sink compound was used to improve the thermal conductance from glass to the thermocouples. The thermocouples were covered so as to shield them from direct sunlight and insulate them from surrounding air. Plant temperatures are probed with smaller thermocouples. A relative humidity sensor (HOBO-RH relative humidity logger, Onset Instruments Corporation) was placed at the center of the greenhouse above the canopy. Temperatures were also monitored at various soil depths (0.01m, 0.05m, 0.10m, 0.25m and 0.50m).

A flow sensor (MK515-P0 Flow Sensor, Signet Scientific Inc.) was installed in the heating water pipe to measure the rate of hot water flow through the system. Thermocouples measured water temperatures before and after it circulated through the heating pipes and fins. AC current sensors (CT-A split-core AC current sensor, Onset Instruments Corporation) recorded the amount of electric power used by the exhaust fans. Linear Displacement Positioning Sensor (LDPS) was installed to monitor the ridge vent movement to log the degree of opening of the ridge vent.

The air exchange rate driven by the cooling fan was calculated from the wind speeds measurements at various positions in front of the fan. An anemometer (Young wind sentry anemometer 03101-5 R.M., Campbell Scientific, Inc.) was used to measure wind speed in front of the fan. From the center to the edge, wind speed decreased approximately linearly. Total volume of exhausted air propelled by the fan was obtained by integrating the wind speed along the radius.

2.3 Data Logging and Signal Calibration

Most sensors were calibrated either by their manufacturer or by us before being used in this experiments. All sensors except the humidity sensor were wired to a data logger (CR23X, Campbell Scientific Inc.). Sensors fall into two groups in terms of time intervals used: those taking samples and storing average values at low frequency, and those at high frequency. The light and temperature are sampled every 30 seconds, and the average values are stored in the data logger every 15 minutes. Environmental control actions, such as opening and closing of ridge vent, turning on/off of fans, and the hot water flow rate through heating pipes, were sampled at a higher frequency (every 10 seconds), and were averaged and stored at the interval of 1 minute.

Since the number of sensors was far greater than the number of input channels on the data logger, a multiplexer (AM32 multiplexer, Campbell Scientific, Inc.) was used to connect sensors and the data logger.

2.4 Weather conditions

Ambient weather conditions, such as the humidity of air, wind speed and direction, were obtained from CIMIS (California Irrigation Management Information System) database. The CIMIS weather station in Davis is about 2 km away from the study site.

2.5 Model Construction and Calibration

To simulate greenhouse temperatures and to optimize temperature control strategies using a modeling approach, model construction and calibration are the most important steps. Models can be distinguished as empirical models and mechanistic models depending on model structures and approaches used to construct models. Mechanistic models are process-oriented models. Empirical models treat the system as a "black box" and describe the relationship between input and output variables using statistical methods.

The approach in this project was a mix of mechanistic models and empirical models. We tried to incorporate the major energy exchange mechanisms in our simulation model, while empirical relationships are employed in submodels. In the following section, important system components were identified in the greenhouse production systems, and important

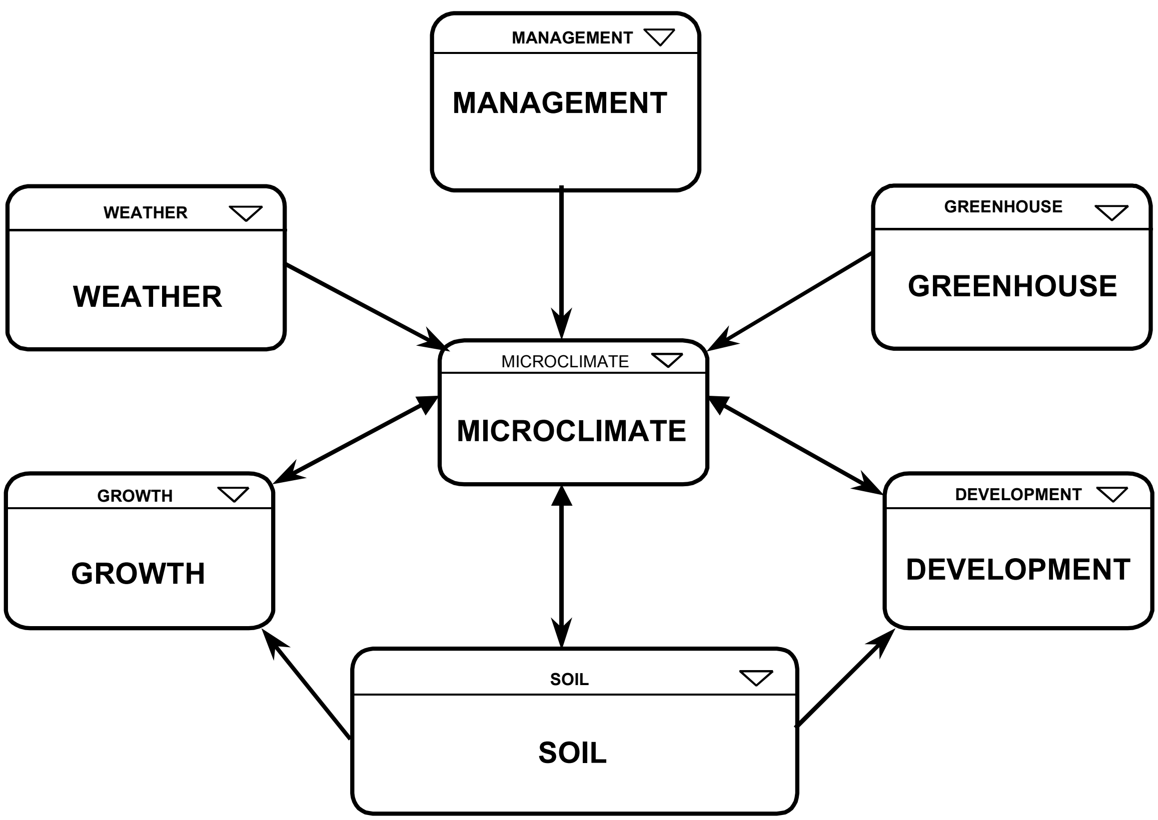

Figure 2 Subsystems in the greenhouse-crop simulation model

energy exchange processes between these components were described, and are quantified using a set of mathematical equations.

2.6 The Model Framework

The framework proposed by Li (1999) was used as a basis for modeling greenhouse temperatures in this project. Several components were identified as major factors that affect greenhouse air temperatures. They are greenhouse structure, weather conditions, crop canopies, soil and environmental management (Fig 2). For constructing a physically-based process model, each of these components was treated as a compartment or a subsystem of the model

The greenhouse structure and the glass represent a boundary for the system, and it is the enclosure that is primarily responsible for the greenhouse effects. The outer air serves as boundary conditions, which might extend to ambient atmosphere when considering the thermal radiation exchange between the greenhouse and sky. Crops growing inside are not only affected by the greenhouse temperature, but also exert influences on greenhouse microclimate. Soil acts as a thermal buffer, it absorbs thermal energy during the day and releases it in the night. The soil can be subdivided into layers, and thermal exchange takes place as a soil heat flux when there is a temperature gradient in soil layers.

Crop growth and development were our primary concern, as they define crop productivity and timing. These determine the economic return of the greenhouse production systems. The greenhouse environment control dictates the energy cost, which greatly depends on the temperature set point and the weather conditions. A good strategy for greenhouse environment control should maximize the net profit from growing a particular crop in the greenhouse. Since crop responses to the greenhouse microclimate consists of complex processes, and greenhouse microclimate and the energy requirement for its control are also complicated, simulation and optimization of this production system is a challenge.

2.7 The Physical Processes of Thermal Exchange

The processes of thermal energy exchange among the greenhouse, the surroundings and the greenhouse components are illustrated in Fig 3. A greenhouse system consists of several components: the cover, inner air, plant canopy and soil. Energy exchange between these components takes three forms: radiation, conductance and convection. Thermal conduction happens between two objects with direct surface contact, convection occurs as a results of mixing of air molecules and eddies. Radiation happens between objects without direct contact and can penetrate through air, glass and crop canopy. The wavelength of the radiation separates this into short wave and long wave radiation, or solar radiation and thermal radiation. Solar radiation is the primary energy input for the greenhouse system, which is composed of direct radiation (or beam radiation) and indirect radiation(or scattered radiation).

The energy exchange at the interface between air and solid objects takes place as the sensible heat and latent heat (if there is a phase change of water). Thermal exchange in the form of sensible heat and latent heat can occur in the boundary layer of leaves and at soil surface. Since soil is a large thermal pool, heat flux in soil can have a great impact on greenhouse energy balance. Thermal exchange can occur naturally or driven by environmental control devices (i.e., heating and cooling).

2.8 Mathematical Models

The thermal status of all other greenhouse components played a role in determining the greenhouse air temperature. The mechanistic model started with an energy budget

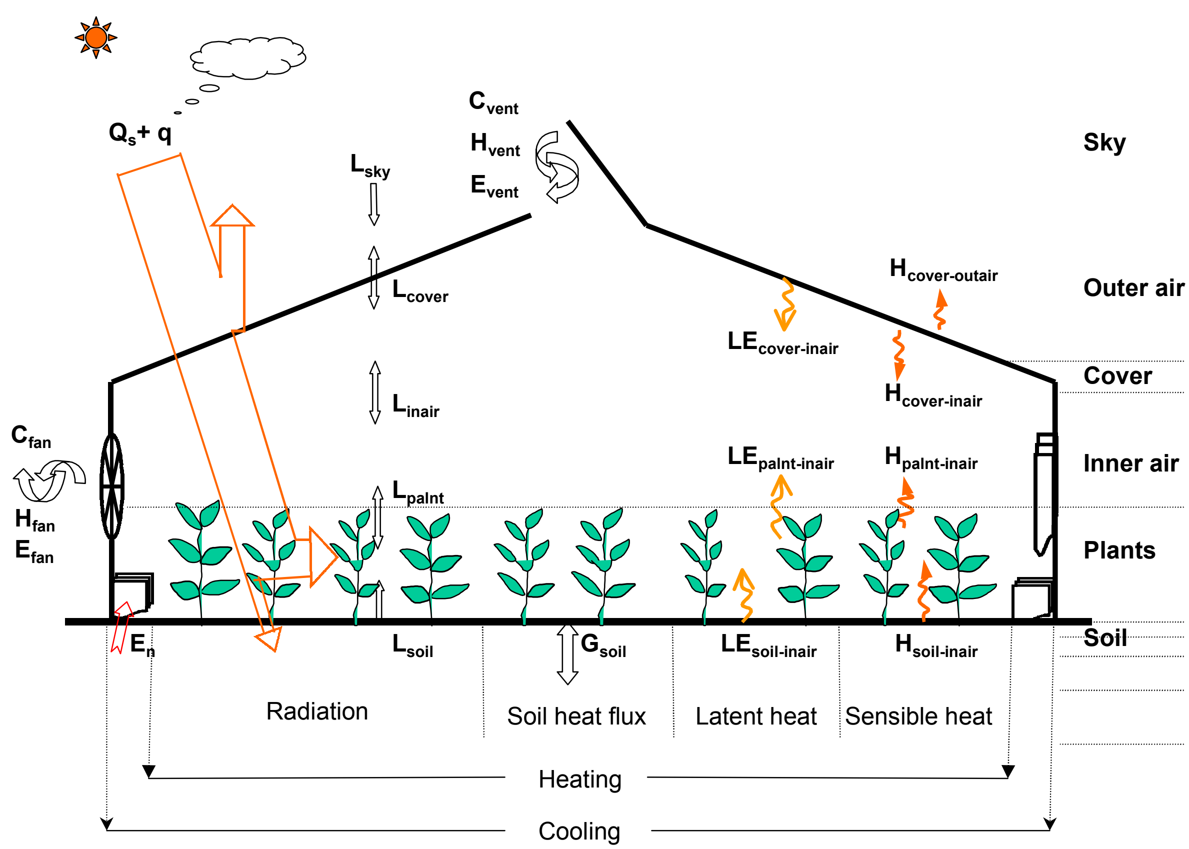

Figure 3 A schematic representation of physical processes of energy exchange in greenhouse crop production systems

analysis for each compartment. The thermal status of all compartments was represented by following differential equations:

$$Z_c c_c \frac{dT_c}{dt} = (Q_s\, a_c\ + q\, a_q) + \Delta L_{cover} - H_{cover-outair} - H_{cover-inair} - LE_{cover-inair} - LE_{cover-outair} \quad (1a)$$

$$Z_i c_i \frac{dT_i}{dt} = \Delta L_{inair} + H_{cover-inair} + H_{plant-inair} + H_{soil-inair} - H_{vent} - H_{fan} + En \quad (1b)$$

$$Z_p c_p \frac{dT_p}{dt} = (Q_s + q)\ \tau_c\ a_p + \Delta L_{plant} - H_{plant-inair} - LE_{plant-inair} \quad (1c)$$

$$Z_{s_0} c_{s_0} \frac{dT_{s_0}}{dt} = (Q_s + q)\ \tau_c\ \tau_p\ a_s + \Delta L_{soil} - H_{soil-inair} - LE_{soil-inair} - G \quad (1d)$$

where T_c, T_i, T_p and T_{so} are temperatures of the cover, inner air, plant canopy and soil surface respectively. Z_x, c_x are the average height and thermal capacity of the compartment x. H_{x-y} and LE_{x-y} are the sensible heat and latent heat exchanges between compartment x and y. Because of the sign convention, $H_{y-x} = - H_{x-y}$ and $LE_{y-x} = -LE_{x-y}$. En is the thermal energy input for heating, and G is the ground heat flux density between the top soil and subsequent soil layers. a_x and τ_x are the absorption coefficient and transmittance coefficient of compartment x to the short wave radiation. a_c and a_q represent the absorption coefficient of glass to the direct and diffuse radiation respectively.

For the soil compartment, only top soil temperature is described in equation (1d). The soil heat flux density at the surface (G) is:

$$G = 2k_{s_0}\left[\frac{T_{s_0} - T_{s_1}}{Z_{s_0} + Z_{s_1}}\right] \quad (2)$$

which is determined by soil heat conductivity and temperature gradient at top layer of soil. The thermal status of other soil layers needs to be treated separately. Soil temperatures at various depths can be simulated with the following differential equation:

$$Z_{s_i} c_{s_i} \frac{dT_{s_i}}{dt} = 2k_{s_i}\left[\frac{T_{s_{i-1}} - T_{s_i}}{Z_{s_i} + Z_{s_{i-1}}} + \frac{T_{s_{i+1}} - T_{s_i}}{Z_{s_i} + Z_{s_{i+1}}}\right] \quad (3)$$

where i represents the i^{th} sub-layer of soil, T_s is the soil temperature, c_s is the volumetric specific heat, k_s is the thermal conductivity and Z_s is the thickness of soil layer.

2.9 Model Calibration and Simulation

Items in the side of equations (1a) through (1d) represent the energy exchange between compartments in the form of radiation, sensible and latent heat, and ground heat flux. The methods for calculating these are not discussed here in depth. The large number of parameters and submodels involved made it impossible to calibrate all models and parameters in the time at hand. Models constructed by others were used whenever feasible. Li (1999) reviewed and complied a set of models for energy budget equations of greenhouse components, these values were used here.

There are several ways to calibrate parameters. For a process where input and output data are known, and the model prototype is clear, model parameters can be estimated by fitting the the model to experiment data using statistical methods. For a series of processes where the output from one model is used as the input of another model, and the intermediate variables are missing from observation, a systematic fitting can be used. This method was used to determine a set of parameters in models which ensured the best fittings between the simulated and observed values of key state variables.

By solving the above system of differential equations numerically, the thermal status of various greenhouse compartments can be obtained. The dynamic simulation software Stella (High Performance System Inc.) was used to do the numeric simulation. Stella was used to graphically simulate all state variables and intermediate variables.

3. Project Outcomes

3.1 Simulation model

The implementation of the simulation model for the combined system (greenhouse and crop) resulted in an extremely complex model. Below we describe the resulting system and it's output. One of the biggest problems with the size and complexity is that the simulation system requires so much computer resources that it can only run for short time-frames on a high-end computer work-station. The extensive requirement on computing resources restricts this model from being used for the real time greenhouse control.

The entire system can be illustrated by the diagrams that show the variables and their interconnection (Figs 4 - 6). It should be noted that each arrow represents a mathematical relationship, while each circle or square represents a variable.

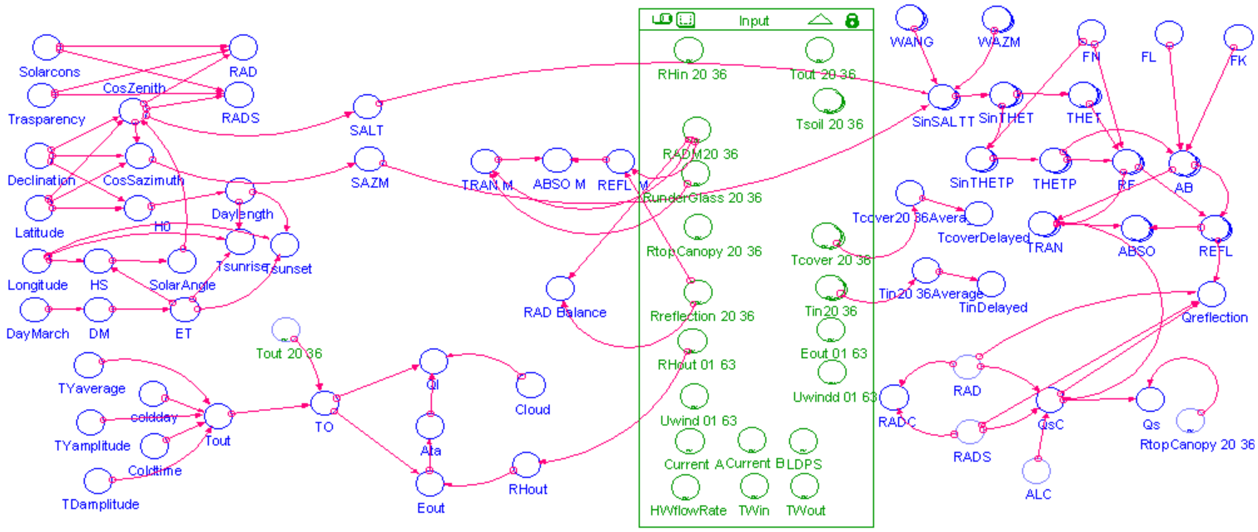

Figure 7 Weather conditions and greenhouse structures module.

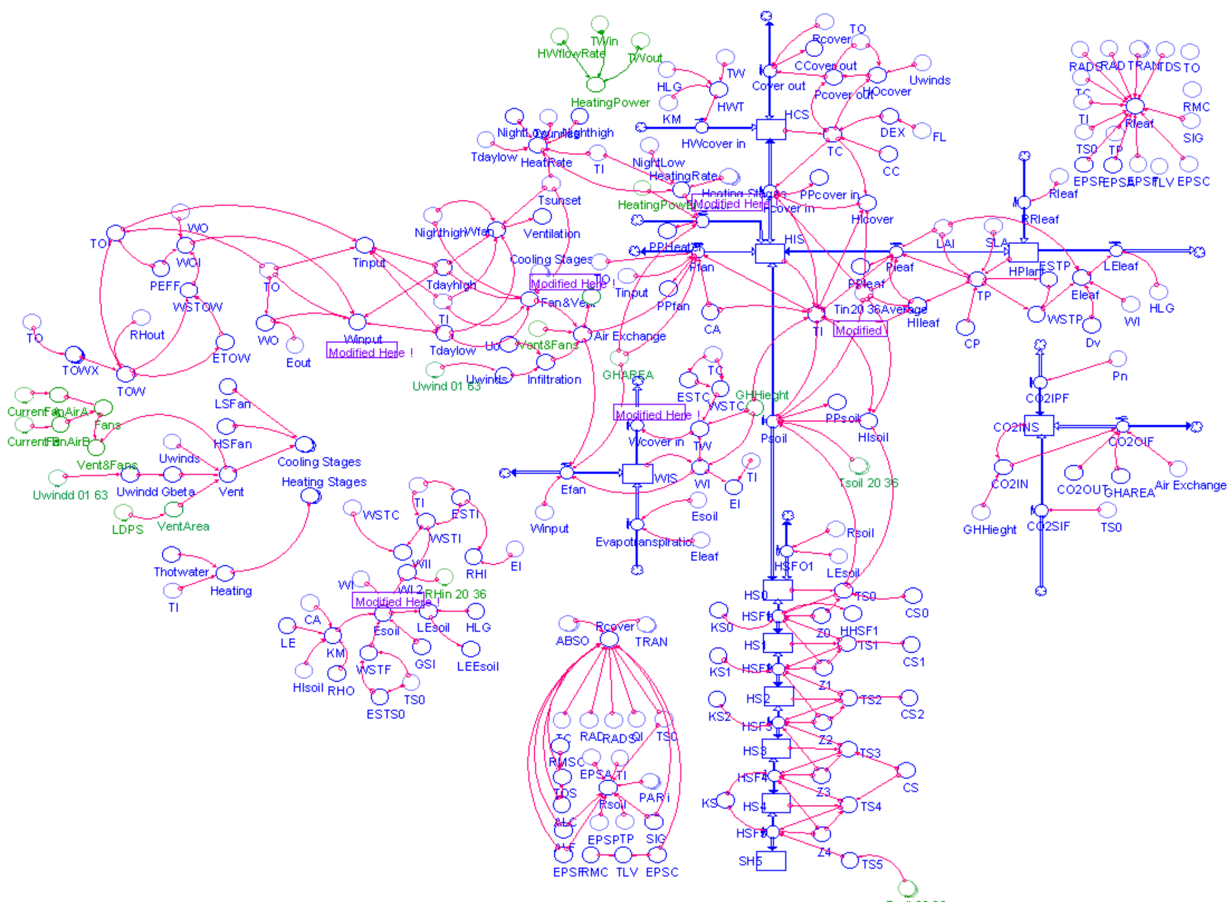

Figure 8 Greenhouse microclimate Module

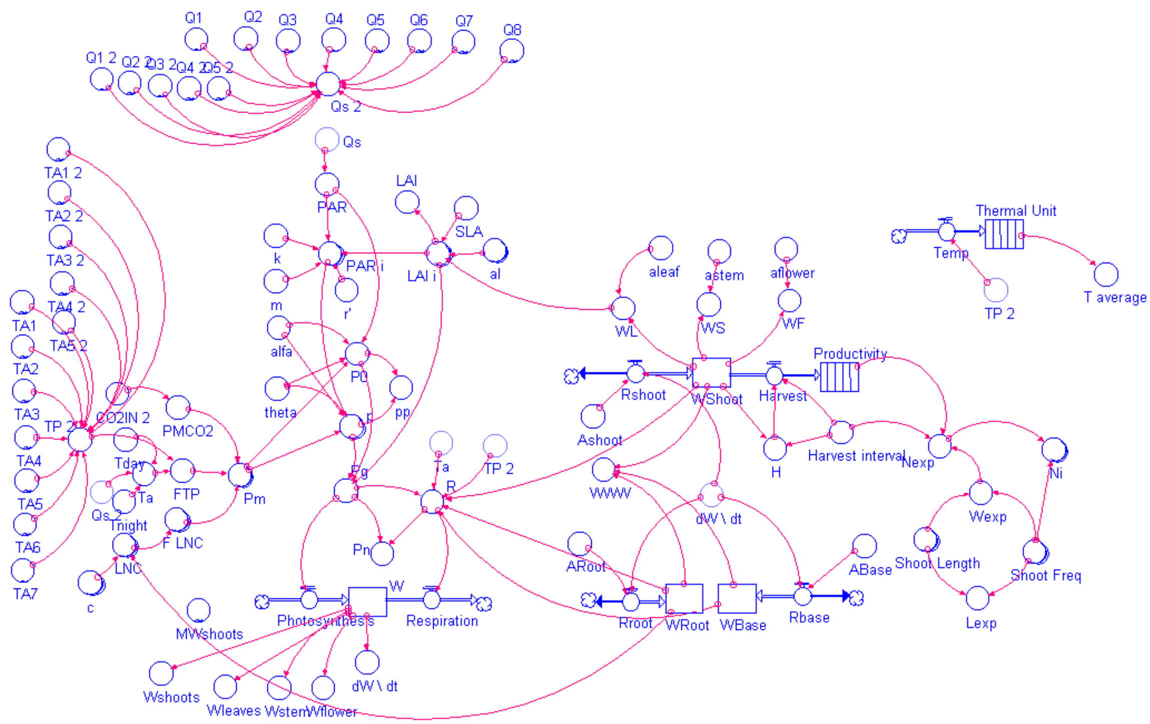

Figure 9 Crop module

Weather conditions and greenhouse structures represent the boundary conditions of the greenhouse systems. The most important elements of weather conditions include solar radiation and ambient air temperature. Other factors, such as humidity, wind direction and speed, also play an important role in determining the energy exchange between the greenhouse and the outside. These variables are used as inputs into the greenhouse microclimate model (Fig 4). They can be either measured or simulated. The variables in the green box are measured weather conditions and greenhouse environmental control actions registered with various sensors. Under some circumstances, solar radiation and temperature can also be simulated using the geographic location and solar time. For example, solar radiation, the time of sunrise and sunset, can be simulated from the longitude, latitude and day of the year and the time of day when atmospheric transparency is predictable. The annual and diurnal variations of temperature also follow some patterns, which can be approximated with cosine curves with adjustments on amplitude and phase.

A model that includes this approach is very useful in reality, because the model can use geographic location and season as the basic input variables and examine how these variables affect greenhouse energy requirement. This information is particularly important for growers to develop strategic plans, such as site selection of the production bases, greenhouse configuration, crops to be grown and production planning across seasons.

Greenhouse structure is described as a set of parameters, such as floor area, height and orientation of the house, glass tilt angel, optical properties of covering material, etc. The advantage of including these parameters in the simulation model is that it can provide some insights for the greenhouse design, such as what glazing materials are best suited for the local prevailing weather conditions. The fundamental considerations must also link to crop requirements.

The Greenhouse microclimate module (Fig 5) implements greenhouse energy budget equations to simulate the thermal status of various greenhouse components including greenhouse glasses, inner air, crop canopy and soil. It takes the weather conditions, greenhouse structures and environmental control actions as input variables. The temperatures of various component are simulated by solving a system of differential equations dynamically. Because of the gradient of soil temperatures along the depth, soil compartment is divided into sub layers.

The crop module (Fig 6) uses the greenhouse microclimate as input variables to simulate crop productivity under various microclimatic conditions. This is achieved by quantifying how the microclimatic elements affect crop physiological processes such as photosynthesis, respiration and dry matter partitioning. Shoot productivity and quality, which are the determinants of profit, are calculated from the dry matter productivity using a set of empirical models.

3.2 Individual Variables

Clearly it is not feasible to show graphics for every variable that was of interest in this project. Below we describe only those that are of direct interest to temperature management. The work to date has resulted in analysis that cover short periods of time in the winter and the summer. Below we show simulations that result for two representative periods: days 30 to 35 and days 170 to 175.

Global solar radiation

At the end of January and in early February, solar radiation can reach around 1000 umol m^{-2} s^{-1}. On days 30, 31 and 34, measured solar radiation is significantly lower than the simulated values. For the day 32 and 33, which were clear days, simulated and measured values are very close (Fig 7).

At the end of June, solar radiation can reach around 2000 umol m^{-2} s^{-1}, almost the double of the winter values. The model does much better job when there are no clouds; under these conditions the simulated radiation level agree perfectly with measured value.

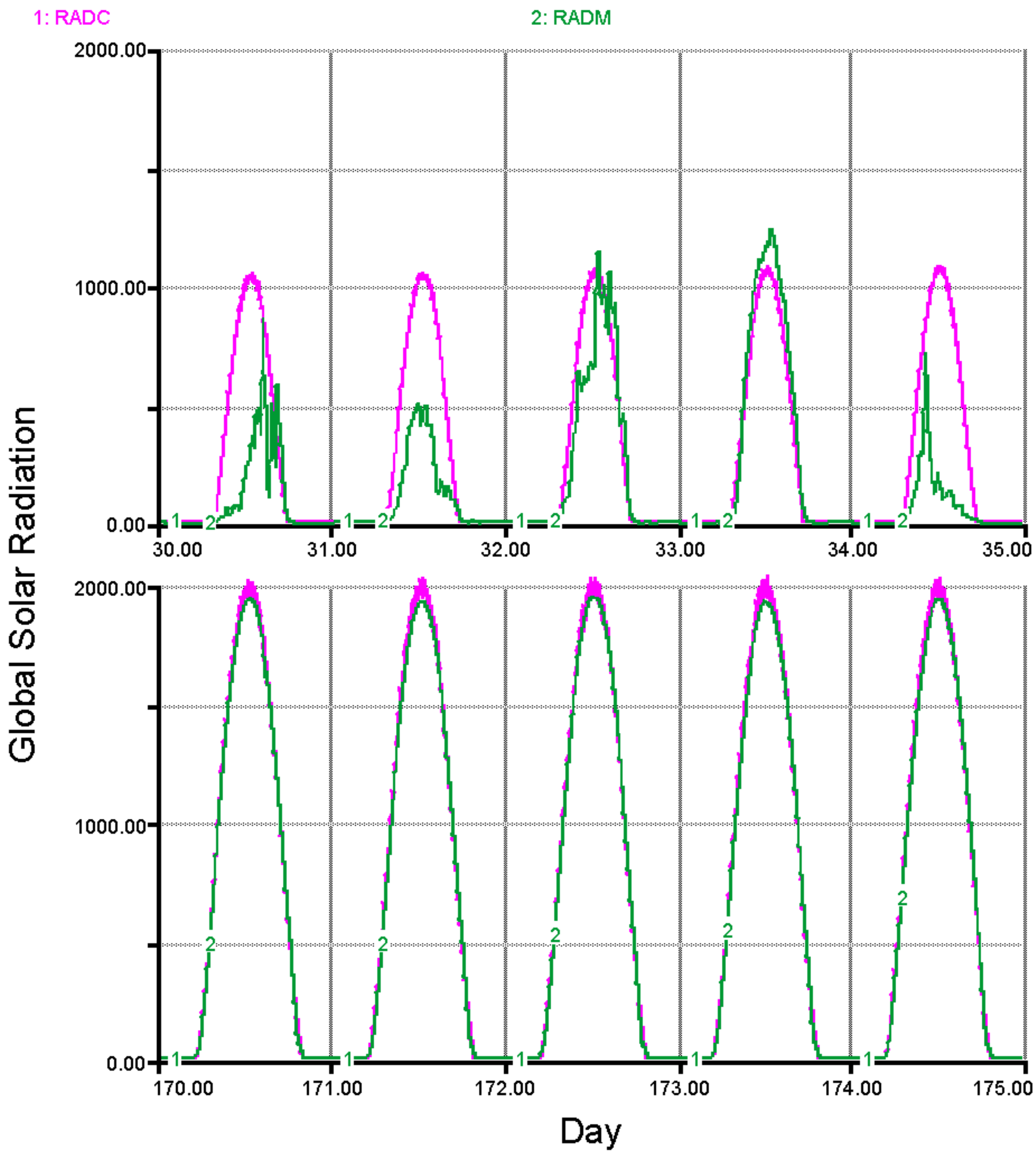

Figure 10 Simulated vs Measured global solar radiation
(RADC – simulated global solar radiation; RADM – measured global solar radiation)

Short wave radiation: direct and scattered solar radiation

Since the model does not consider the effects of clouds, RADC represents the potential solar radiation, which is the maximum light level that can be expected. The direct radiation consists of about 2/3 of total radiation, and the remaining 1/3 comes from scattered radiation. For the Central Valley of California, the simulated RADC is usually higher than the real measurement for winter days. This is because the prevailing climate in this area is midterranian climate, characterized by the wet mild winter and hot dry summer. Because of the presence of clouds, this model usually overestimate the radiation level during the winter, but it does a fairly good job for summer days (Fig 8).

In comparison with winter conditions, the total summer solar radiation level is almost doubled, increased from around 1000 to 2000 umol m^{-2} s^{-1}. Furthermore, the composition of the total radiation is also different: in winter, short wave radiation consists of 2/3 direct radiation and 1/3 scattered radiation, while in summer, ¾ of short wave radiation comes from direct solar radiation and only ¼ is from scatted radiation. This makes sense because in summer the pathway of the beam is shorter as a result of higher solar angle, while in winter the more radiation is scattered in the longer path of solar beam in the atmosphere.

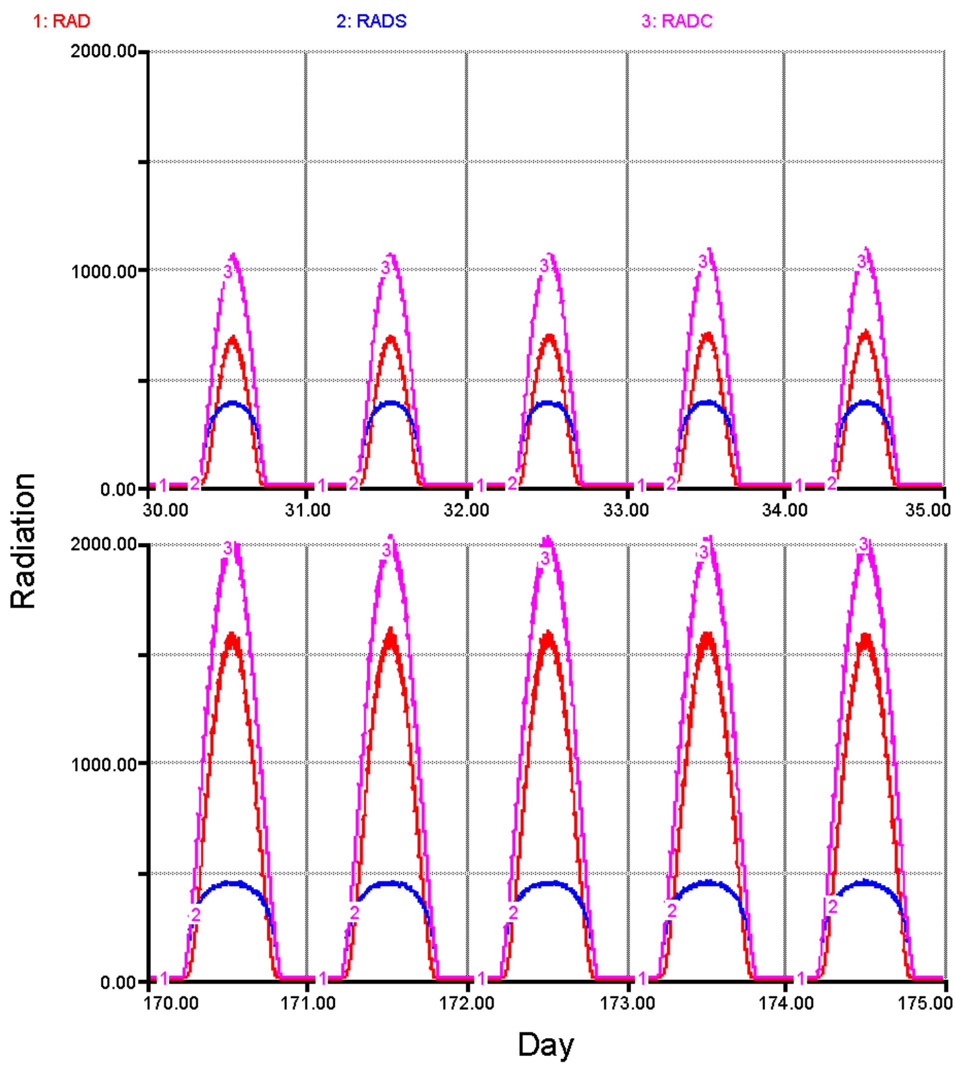

Figure 11 Short wave radiations: direct and scattered solar radiations (RAD = direct solar radiation; RADS= scattered short wave radiation; RADC= global short wave radiation, which is the sum of RAD and RADS)

Solar radiation under the glass and above crop canopy

As indicated above, the simulated solar radiation under the greenhouse glass is based on the simulated global radiation. Thus there are currently significant errors for cloudy days (e.g. Fig 9; day 30, 31 and 34). For clear days, the simulated radiation under the greenhouse glass is very close to measurements.

The radiation that reaches the canopy is lower than that measured directly under the glass. This is caused by shadows of the greenhouse structure cast on the light sensor locatd on the top of crop canopy. For sensors that were placed directly under the glass, no such shadows resulted on the sensor. By comparing the difference, solar radiation intercepted by greenhouse structures can be estimated.

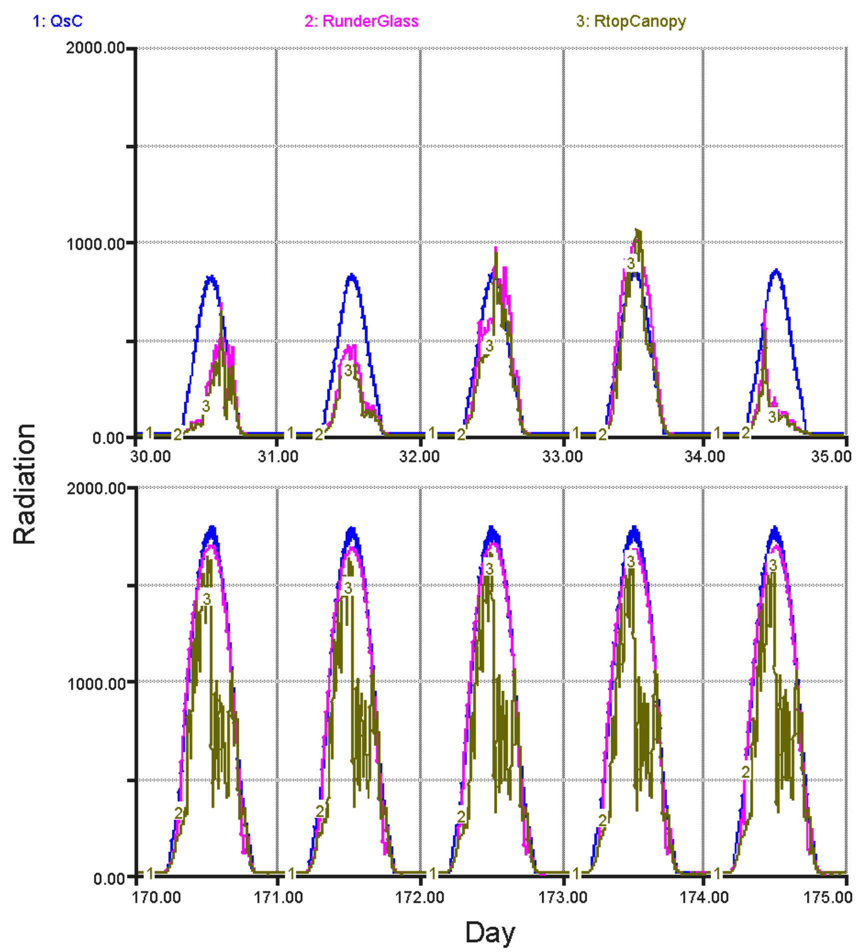

Figure 12 Solar radiation under the glass and above crop canopy : Simulated vs Measured (QsC – simulated solar radiation under the greenhouse glass; RunderGlass – measured solar radiation under the greenhouse glass; RtopCanopy – measured solar radiation above crop canopy)

During the summer, the simulated solar radiation under the greenhouse glass is very close to the measurement when there are no cloud effects. The radiation measured at the top of canopy is significantly lower than those measured just under glass, indicating shading by greenhouse structures reduces the amount of solar radiation available for photosynthesis. At the sensor location, shading occurred mostly in the afternoon. In the morning when there is no shading, the radiation level at the top of canopy is very close to that measured under the glass.

Reflected short wave radiation by glass

The simulated reflected shortwave radiation (Fig 10) was calculated according to the simulated global short wave radiation. Therefore, it much higher than the real situation when it is cloudy. However, even for clear days (day 32 and 33), reflection is still

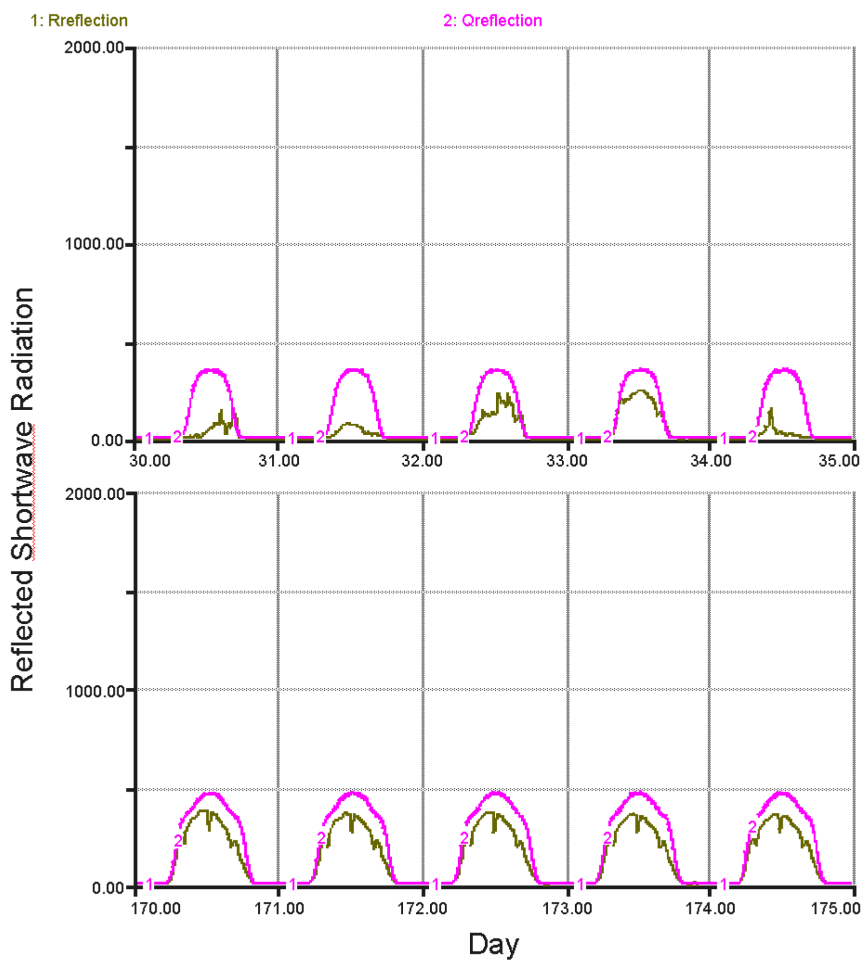

Figure 13 Reflected short wave radiation by glass: Simulated vs Measured (Rreflection -- measured reflected short wave radiation; Qreflection – simulated reflected short wave radiation)

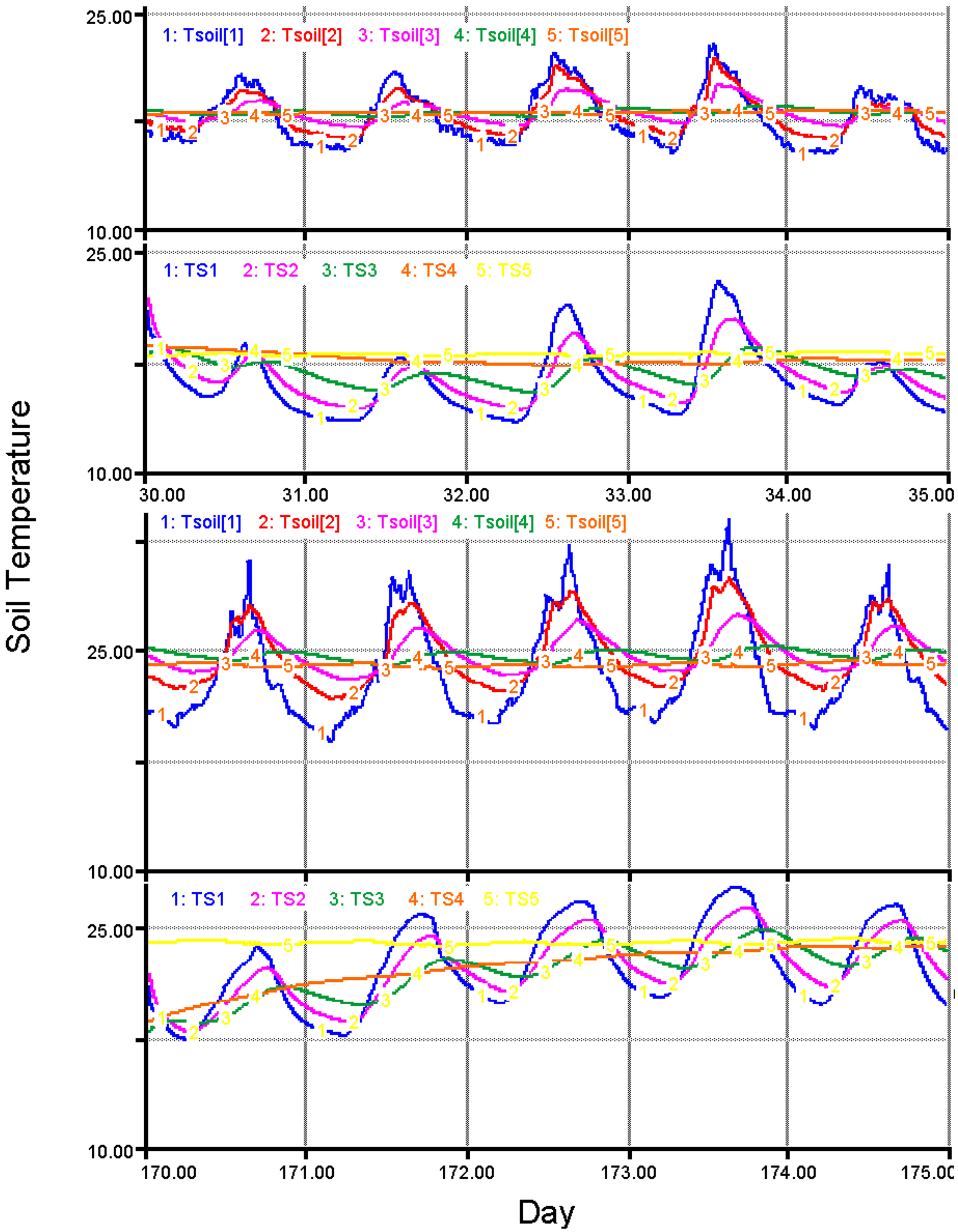

Figure 14 Soil temperatures in the greenhouse at various depths: Measured:TSoil[1] - 0.01m; TSoil[2] – 0.05m; TSoil[3] – 0.10m; TSoil[4] – 0.25m; TSoil[5] – 0.50m. Simulated: TS1 - 0.01m; TS2 – 0.05m; TS3 – 0.10m; TS4 – 0.25m; TS5 – 0.50m.

overestimated, about 25% higher than the measurement.

For the summer, the reflected solar radiation is also overestimated by the model but not to the same extent. The overestimation is most severe during afternoon hours.

It is possible that this is due to the location of the sensor that measured reflection by the glass. The roof glass has two aspects. The other aspect reflects more solar radiation in the afternoon. Therefore, on average the simulation results are acceptable.

Soil temperatures at various depths

Measured and simulated soil temperatures at various depths (Fig 11) follow a diurnal pattern which has greater amplitude the higher the soil layer. Also the lag in the fluctuation increases with deeper soil layers (i.e slower response to temperature changes in the greenhouse above the soil). The temperature fluctuation tends to be greater on clear days than on cloudy days.

The simulated soil temperatures follow the general pattern observed in the measurements, such as the diurnal fluctuations and the phase-lag in deeper soil layers. The simulated soil temperatures are lower than the measurements on cloudy days. For clear day, simulated values agree the measurements very well.

In the summer, the soil temperatures at top layers vary in larger amplitudes than in winter. The temperature at the deep soil (0.5m) stabilizes at around 24.5C, while in winter it is much lower, around 17.5 C.

The same initial thermal values were used as starting point in the simulations for both winter and summer (Fig 11). These values are too high for the winter situation and too low for the summer condition. It takes several days for the simulation to catch up the current condition because this part of the system is very sluggish. This a normal and expected.

Greenhouse air temperature:

The simulated air temperature for the winter data was constantly and systematically lower than the measured values, though the simulated temperature pattern did follow the same pattern (shape) as measured ones (Fig 12, top panel). Because of the number of parameters used in the model and the complex interactions of many processes, we do not know the reason for this at this point.

When the cooling pad was wet during the summer (which is the case for the situation simulated in Fig 12 (bottom panel), the simulated temperature was very close to the measured value. The fluctuations in the curve reflect the activities of cooling fans, as these were turned on and off frequently by the greenhouse computer control system.

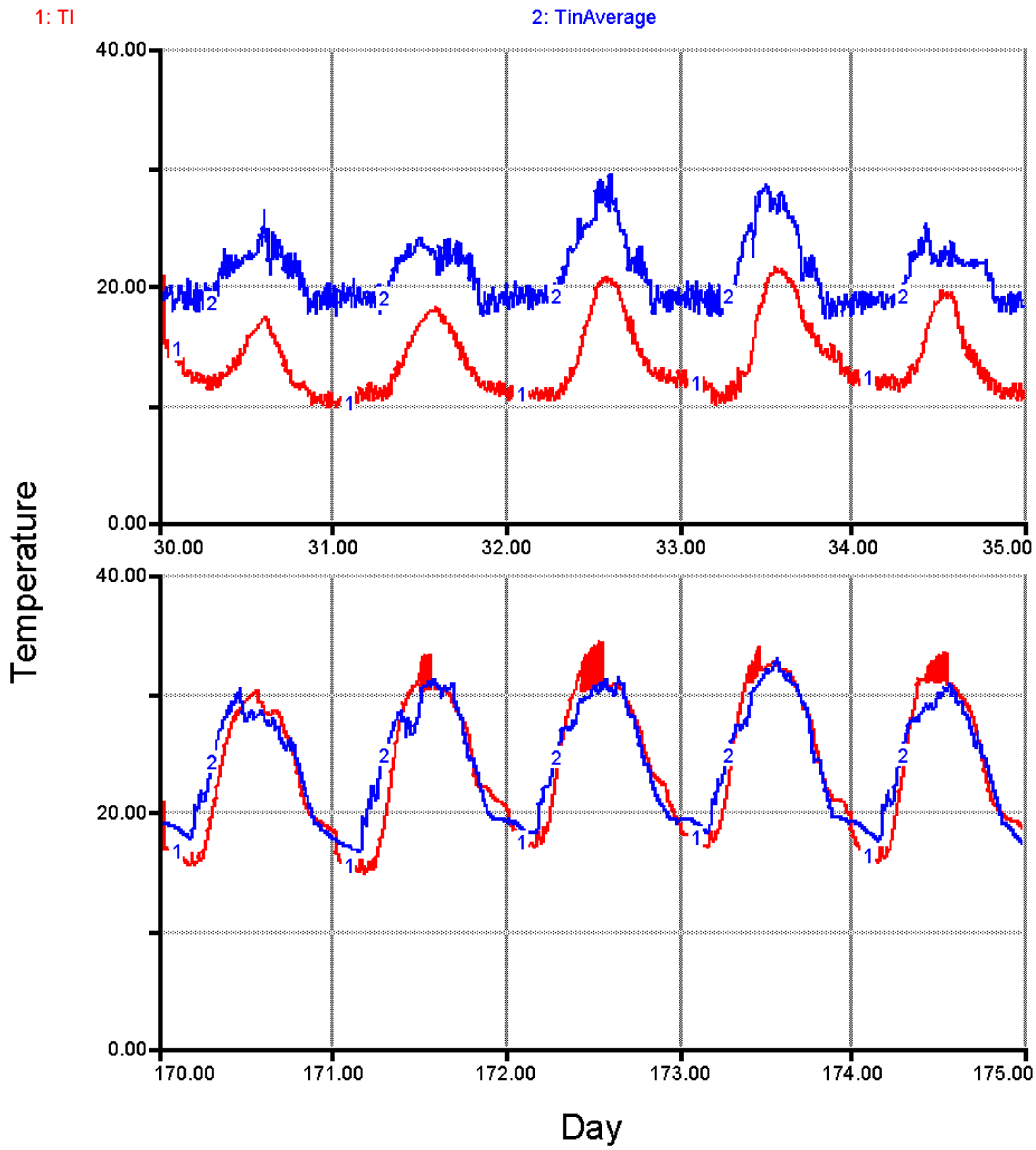

Figure 15 Greenhouse air temperature: simulated vs measured (TI – simulated greenhouse air temperature; TinAverage – the average of measured greenhouse air temperature at 4 points)

<u>Greenhouse glass temperature</u>

Similar to the greenhouse air temperatures, the simulated glass temperature is constantly and systematically lower than the measured values, though the simulated temperature does follow the same pattern of measured values. The lower simulated air temperature may cause the lower simulated glass temperature.

During the summer the simulated glass temperature were slightly lower in the morning than the measured values. The simulation results are much better in the afternoon.

The Relative Humidity

Since the simulated greenhouse air temperature was underestimated during the winter days, the simulated humidity is correspondingly higher than the measured values.

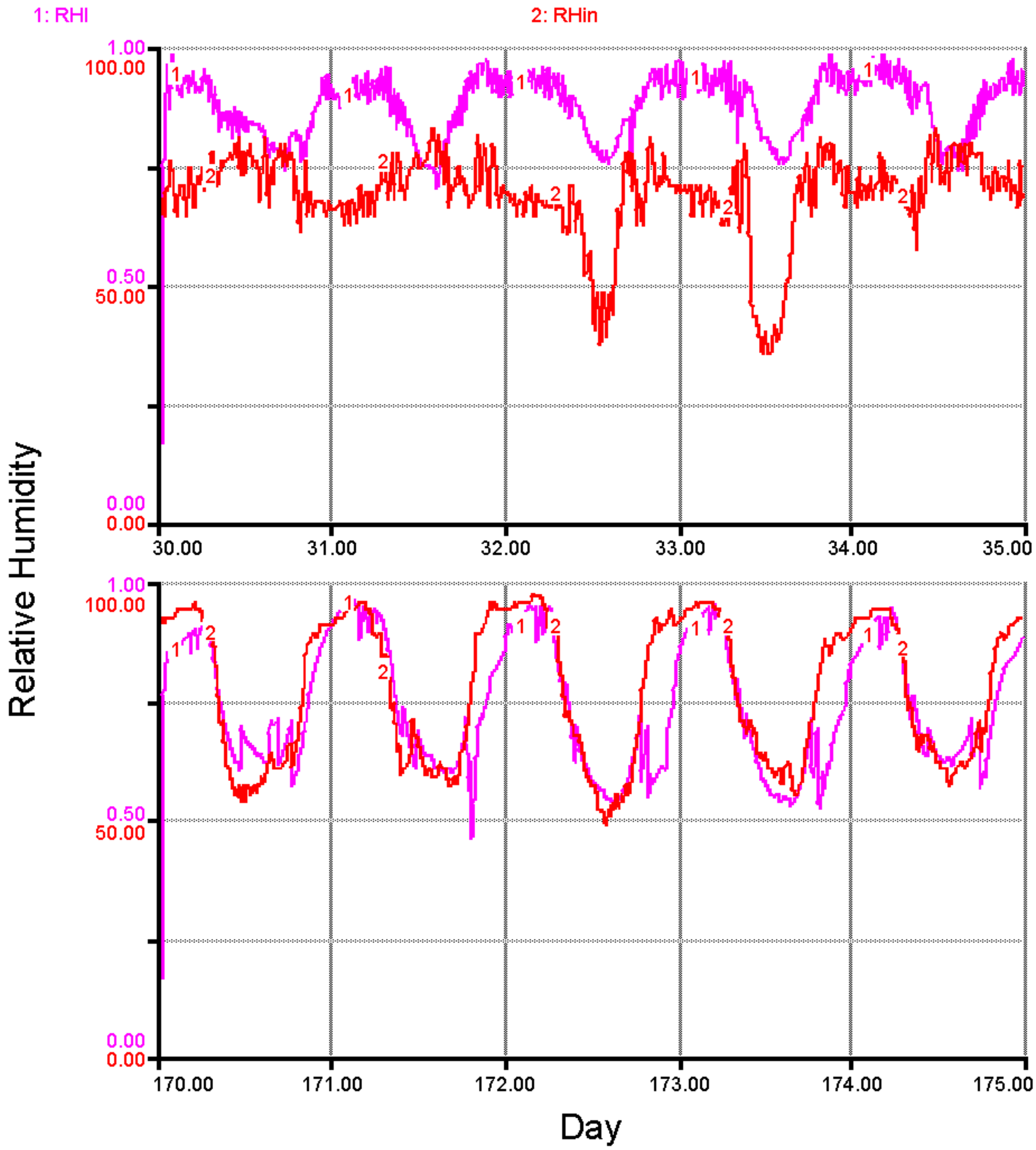

Figure 16 The relative humidity: simulated vs measured (RHI – simulated relative humidity of greenhouse air (as fraction); Rhin – measured relative humidity of greenhouse air (%))

To accurately simulate relative humidity was particularly difficult since relative humidity depends on both thermal exchange and vapor exchange between the system and its surroundings.

For summer simulations, the simulated humidity agrees well with the measurements, probably because the model predicts the air temperature very accurately.

Simulated CO_2 concentration inside the greenhouse

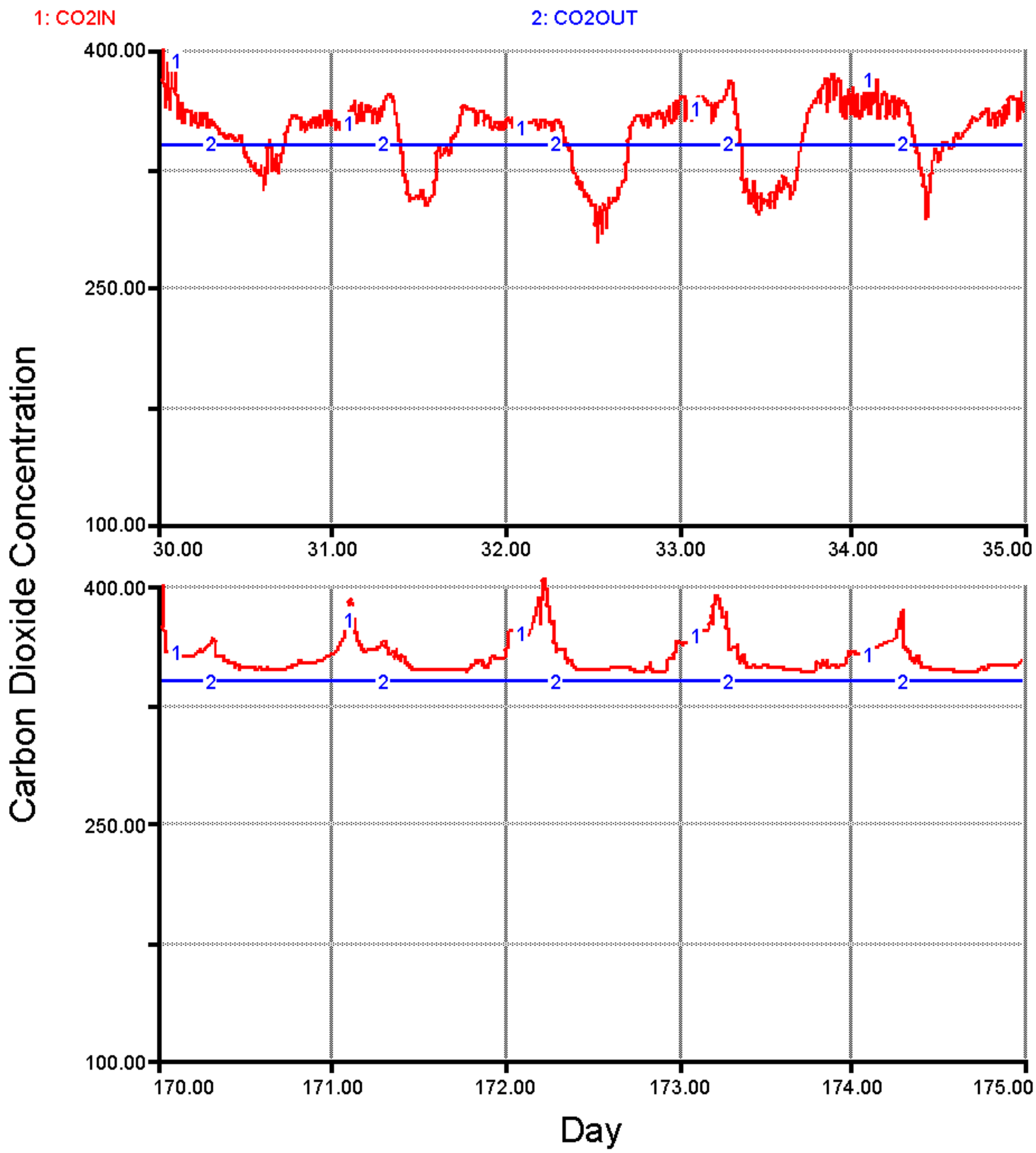

Figure 17 Simulated CO_2 concentration inside the greenhouse (CO2IN -- CO_2 concentration inside the greenhouse; CO2OUT -- CO_2 concentration of outside)

CO_2 concentration varies in a clear diurnal pattern inside the greenhouse. In the simulation, the reference CO_2 concentration was set at 340ppm, the simulated CO_2 concentration inside the greenhouse resulted from several processes: air exchange through ventilation and infiltration, photosynthesis and respiration of plants, and respiration of soil microorganisms. In the night, CO_2 concentration is above the reference level because of respiration and smaller air exchange rate between greenhouse and its

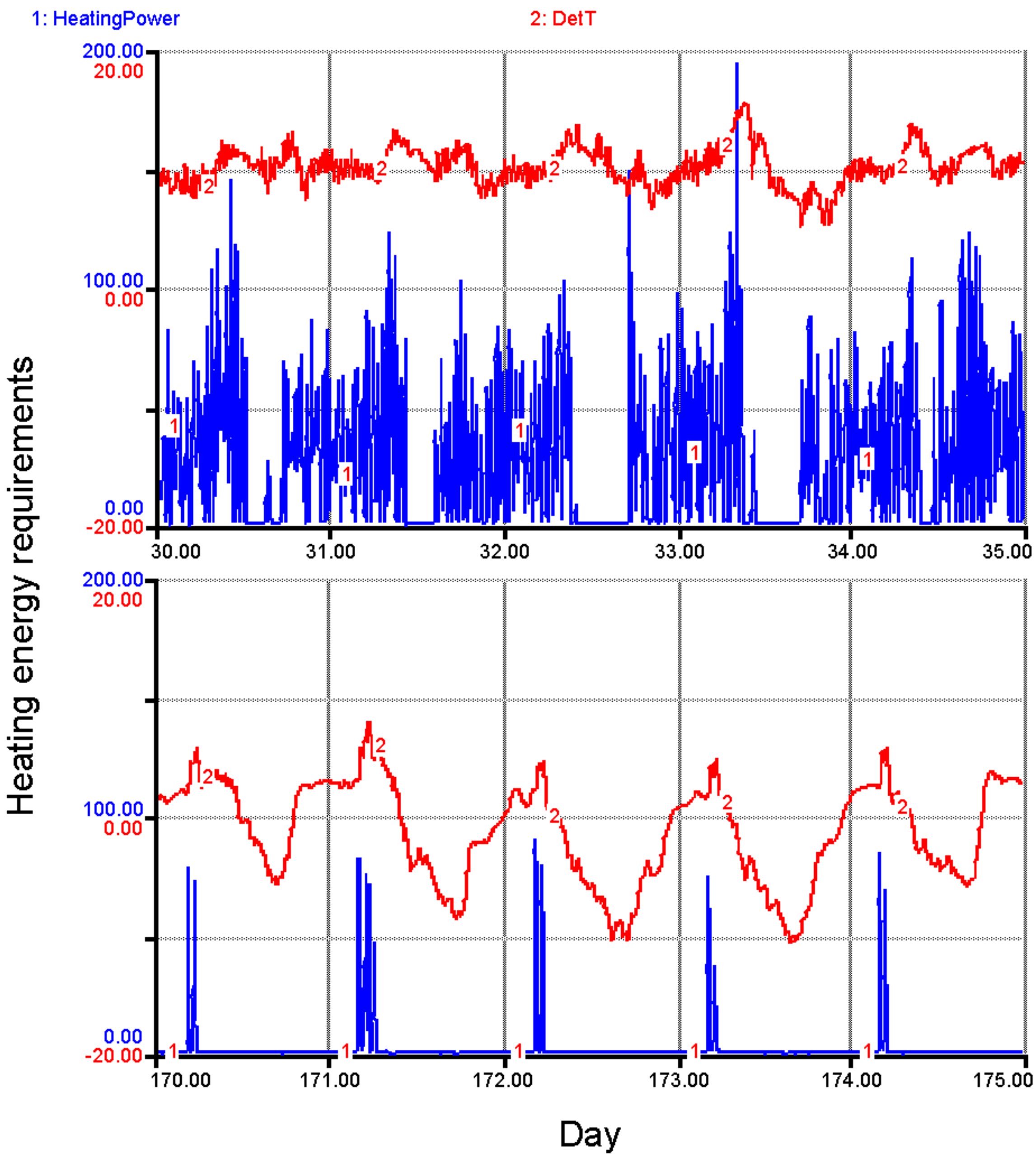

Figure 18 Heating requirement vs inside and outside temperature difference (HeatingPower – the energy pumped into greenhouse for heating (kW); DelT – the difference between inside temperature and outside temperature (C))

environments. During winter days, CO_2 is depleted partially due to photosynthesis of leaves. During the summer this is not seen because the frequent venting prevents the draw-down of the CO_2 concentration.

Heading requirement vs inside and outside temperature difference

For winter days, temperature inside the greenhouse was 10 C higher on average than the outside temperature due to the fact that the heating system was turned on very frequently (Fig 15). However, for clear days (day 32 and 33), the solar radiation around noon was relatively strong and the temperature inside greenhouse was even higher than outside without turning on heating system.

Even in the summer the greenhouse heating was activated occasionally during the night when outside temperature is significantly lower than the inside greenhouse temperature set-point. This usually occurred at dawn before the sunrise. However, the greenhouse temperature is higher than the outside in most of time during the day, the cooling is the more important issue for this period.

Cooling energy requirement vs inside and outside temperature difference

Although some cooling was required each day during the winter (Fig 16. top panel) far more energy was invested in heating. During the day time the energy used for cooling was over 1000W, and cooling fan was on most of time during the day. There was no cooling requirement during the night. The model simulates this in accordance with what was observed.

In general, cooling for the greenhouse being simulated was more efficient than heating and required less energy.

During the day time during the summer the energy used for cooling was over 1000W, and cooling fans were on most of time during the day.

3.3 Model Validation

At this point we cannot come to the conclusion that the model is validated. This is an unfortunate consequence of the fact that we had a significant interruption in the time that the key scientists was able to devote to this project.

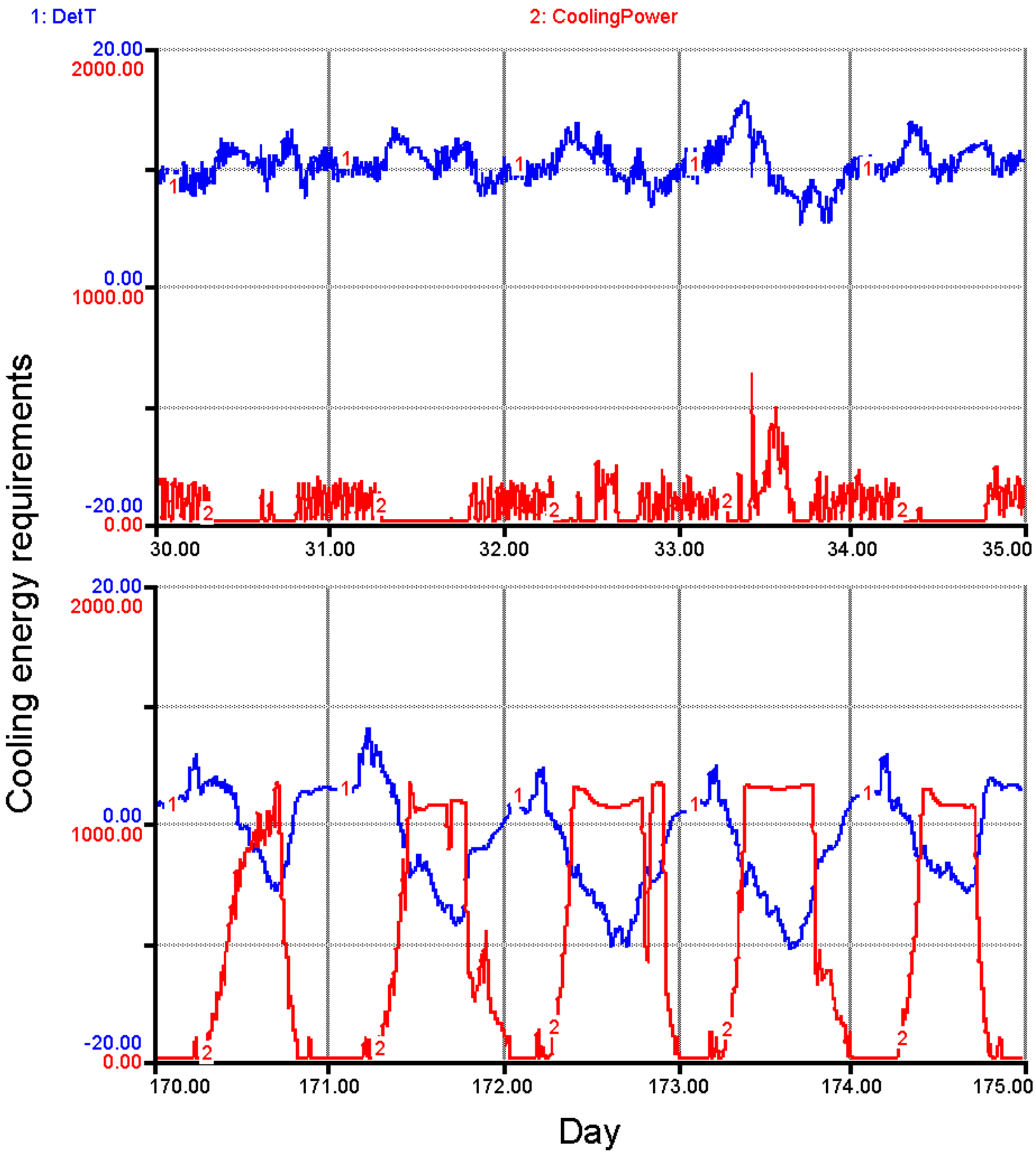

Figure 19 Cooling energy requirement vs inside and outside temperature difference (CoolingPower – the energy used for greenhouse cooling (W); DelT – the difference between inside temperature and outside temperature (C))

3.4 Development of a tool for greenhouse house temperature management for rose growers.

In keeping with our objective to develop tools that growers could use for temperature management, we developed software that allows growers to deal with the consequence of needing to use different temperature set-points in their greenhouses as a consequence of markedly higher energy costs during the winter of 2000/2001. As our modeling work was done for cut-flower rose, this part of the project was aimed at greenhouse cut-flower rose growers.

The portion of the rose model used for this work was the part that allows calculation of the dates for specific developmental events based on greenhouse air temperature. This model uses a heat unit approach. In earlier work we found that the base temperature for heat unit accumulation in rose is 5.2C. The Rose Development Calculator software (Fig 17) allows the grower to select a rose variety from a database. The grower then enters the average day temperature, average night temperature, and day-time duration, and the program calculates the average 24-hour temperature. The daily accumulated heat units are calculated using this value. The grower selects which developmental stage is to be used as the fixed date and provided a date for this event. By pressing the "Calculate"

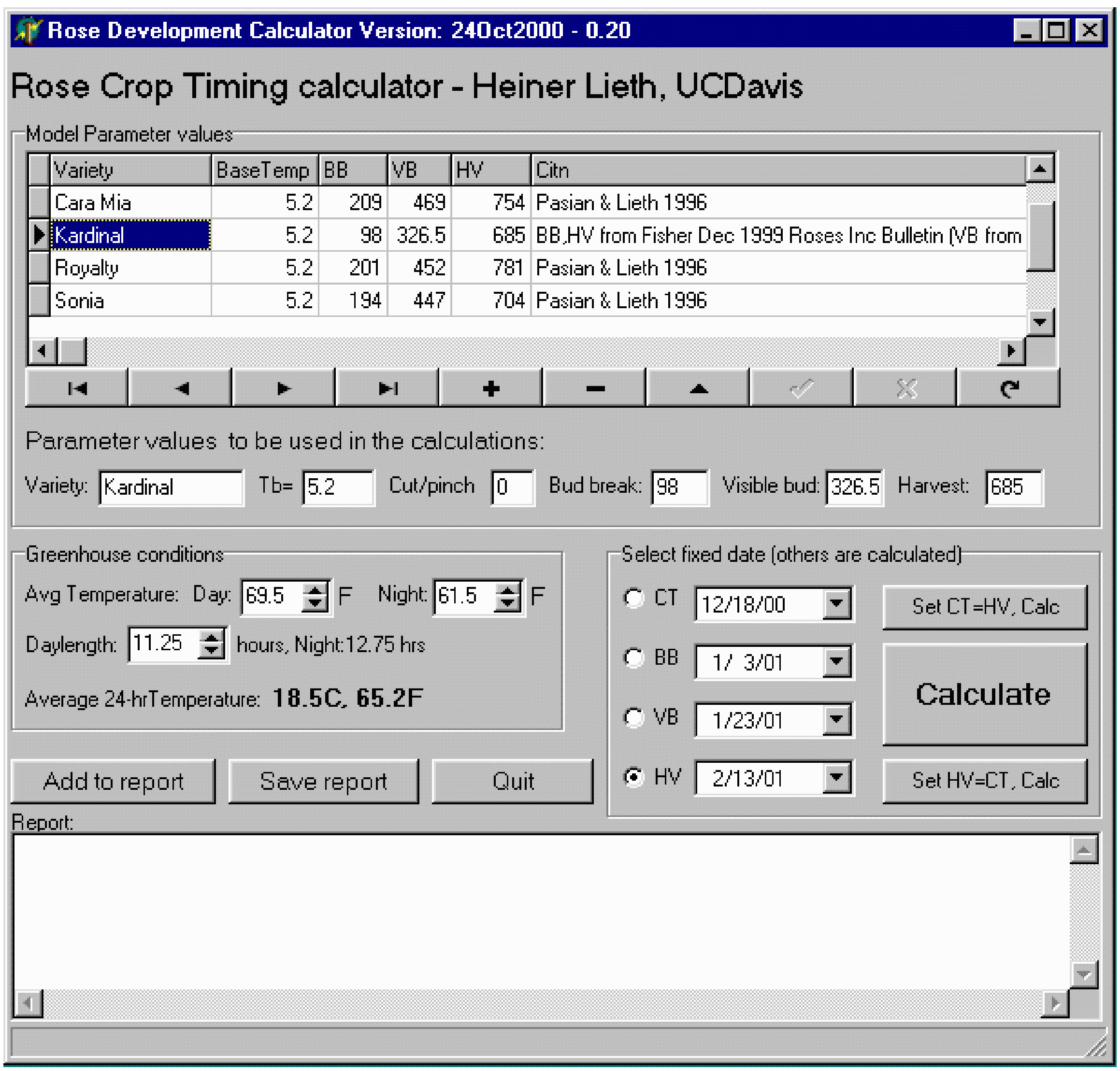

Figure 20 Rose Corp Timing calculator software developed for rose growers.

button, all dates for the other developmental events are calculated.

Typically a grower would select HV, the targeted harvest date (which may be a holiday such as Valentine's day). The CT date would then be the date on which the grower would have to initiate a pinch or previous harvest so that the next generation of shoots will reach HV on the desired date. Along the way, the grower can observe the other developmental events to verify that the crop is on time. Details for use of the model and software, as well as a facility for disseminating the software are found at the following web site: http://Lieth.UCDavis.edu/Research/HU/RoseTime/

This site also provides a guide to the use of the software, photos to show the grower the identifiable stages of development, as well as the current version of the software. Currently on Windows operating systems are supported.

4. Conclusions and Recommendations

This project has resulted in the development of a greenhouse crop simulation system implemented in the simulation software Stella. This simulation system is very complex and allows observation of key greenhouse environment parameters. This is a research tool and as yet not validated for general purpose. In fact, it is unlikely that a general purpose version of this possible. As yet we have also not reached the point where we can use it to extensive energy simulations which would be needed to come to conclusions about issues related to energy efficiency.

We were able to spin off some of the technology in this research project to develop a grower tool that predicts rose crop productivity in relation to greenhouse air temperatures. This tool provides growers with a valuable tool to determine the effect of temperature adjustments on crop timing. This is particularly important during the current energy crisis where many growers will be implementing radically lower temperature set-points so as to reduce energy costs.

Appendix B: Awardee Rebuttal to Independent Assessment

The FAR assessment is basically correct. I would just add two points:

1. The use of mathematical models in greenhouse environment control computers is still increasing and the work that was carried out in this project is still relevant. Although the feasibility of implementation of the particular model developed in this project is small at this time, it is likely that a smaller version of the model could be of significant interest. Alternately, since computer technology is ever improving, it may well be that the technological advancements may result in improved feasibility in the future.
2. Technology transfer is continuing and future training sessions for growers are planned in the use of the system. At various times growers have sought out information that the software tool is able to furnish and at those time individualized training is provided to help growers.